Magn tic Fluidic Seal with Improv d Pressur Capacity

BACKGROUND OF THE INVENTION

1. Field of the Invention

[0001] The present invention relates generally to magnetic fluid seals. Particularly, the present invention relates to multi-stage magnetic fluid seals.

2. Description of the Prior Art

[0002] Magnetic fluid rotary seals have been widely used in vacuum applications over the past twenty years. The basic structure of the seal has at least one magnet, a rotary shaft, and pole pieces fastened within a housing. The magnet, the pole pieces and the shaft form a magnetic circuit with air gaps. A magnetic fluid is attracted to the air gap and forms the dynamic sealing between the pole pieces and the rotary shaft. The sealing between stationary parts such as between a pole and the housing is usually accomplished by using a rubber O-ring at the radial interface. Modern applications increasingly require magnetic fluid seals with increased pressure capacities. Conversely, as the size of modern applications decreases, smaller magnetic fluid seals having the same pressure capacity are also needed.

[0003] The pressure capacity of a magnetic seal is proportional to the magnetic field within the seal. When the magnetic field is concentrated, or increased, the pressure capacity of the seal also increases proportionally.

[0004] Protrusions or ridges, which are also referred to as stages, projections, teeth, or fins, have been incorporated within the gap between a pole piece and a shaft of a

magnetic fluid seal to concentrate the magnetic field adjacent the pole piece. These ridges can be formed in the shaft, in the pole, or in both the shaft and the pole. As the number of ridges or teeth increases, the pressure capacity of the seal also increases. However, the sustained differential pressure for each stage is proportional to the total flux of the magnetic field even if two pole pieces are used, one on each side of the magnet. Thus, such a magnetic system has an upper limit and saturation develops at a relatively small number of teeth or ridges. At magnetic saturation, an increase in the number of teeth will reduce the flux choking and will better utilize the magnetic flux.

[0005] In situations where magnetic saturation does not exist such as when the magnet is not strong enough or when the pole pieces are increased in size to the limit of the total flux of the magnetic field of the existing magnet, further increases in the number of ridges by increasing the size of the pole piece will result in lesser and lesser increases in pressure capacity. This is so because the magnetic flux field beneath each additional ridge is not strong and centrifugal forces easily throw the magnetic fluid away from the gap.

[0006] To further increase the sustained differential pressure, a seal requires multiple magnets and pole pieces. However, it is not always practical to simply increase the size of the magnetic seal. Attempts have been made to increase the sustained pressure capacity for each stage seal below a pole piece of a magnetic seal thereby increasing the pressure capacity of the magnetic seal without increasing the size of the magnetic seal.

[0007] U.S. Patent No. 3,3620,584 (Rosensweig, 1971) discloses several embodiments of a magnetic fluid seal with knife edges cut into the outer ring pole pieces or the shaft, or both. A plurality of knife edges form a row of right triangles where the acute angles of the plurality of knife edges are aligned in one direction. In another embodiment viewed in cross-section, the acute angles of the knife edges are grouped into two groups. The first group of knife edges has the acute angles aligned in one direction and the second group of knife edges has the acute angles aligned in the opposite direction.

[0008] U.S. Patent No. 4,440,402 (Pinkus,1984) discloses a ferrofin magnetic-fluid seal. The ferrofin magnetic-fluid seal comprises a plurality of concentric, fin-like projections of magnetically permeable material formed on each of a rotating member and a stationary member in a spaced-apart opposing relation defining a plurality of magnetic gap regions. The cross-sectional shape of the fin-like protrusions are rectangular in geometry with parallel sides and a parallel base and top. The dimensions of the fin-like projections are such that the distance between the base and top is greater than the distance between the sides. The fin base is attached to the shaft and the pole pieces. The fin top protrudes into the gap between the shaft and pole pieces.

[0009] *Magnetic Fluids, Engineering Applications* (Berkovsky et al., 1993, p. 138-41) discloses that the pressure differential can be increased slightly when tapered teeth (serving as focusing structures of the magnetic field) are located on both the poles and the shaft, one opposite another. The cross-sectional view of the tapered teeth disclosed in Berkovsky et al. form an equilateral triangle where each leg of the

triangle is the same length. Berkovsky further discloses that a seal with tapered teeth is disadvantageous since the structure must be fixed in both radial and axial directions. Additionally, Berkovsky discloses that, since working gaps are small (about 0.2 millimeters), problems arise with serviceability of shafts and high shaft runout.

[0010] The eccentric location of the shaft and the poles due to high shaft runout causes changes in the working gap in the azimuthal direction, which causes magnetic field intensity changes in the gap between the shaft and the poles. The point at which the gap has increased has a correspondingly decreased magnetic field strength and, thus, a decreased holding capacity of the seal. This decrease may be appreciable. The reduction in sealing capacity due to eccentricity can be more than 80-90%, depending on the level of eccentricity.

[0011] U.S. Patent No. 5,954,342 (Mikhalev, 1999) discloses a magnetic fluid seal apparatus for a rotary shaft. The magnetic shaft sleeve of the apparatus includes a plurality of protrusions affixed thereto. The protrusions are triangularly shaped having an acute angle. The acute angle provides a frictional bond with the magnetic fluid. One group of sleeve protrusions that aligns with one pole has acute angles lined up facing in one direction. The second group of sleeve protrusions that aligns with the second pole has acute angles lined up facing the opposite direction.

[0012] Even though the prior art knife edge stages help focus the magnetic flux lines in the air gap and thus slightly increase the differential pressure capacity, they also increase the magnetic choking effect with regard to the density of flux lines at

the knife edges, which is limiting. Where double, opposed knife edges are used, misalignment causes a decrease in the magnetic force field.

[0013] Therefore, what is needed is a multistage magnetic fluid seal that provides a higher pressure capacity than conventional magnetic fluid seals of similar size. What is also needed is a multistage magnetic fluid seal that focuses the magnetic force field and provides a decreased choking effect. What is further needed is a multistage magnetic fluid seal having stages on both opposed surfaces of the rotary seal that is much less sensitive to axial misalignment than conventional multistage seals having stages on both opposed surfaces of the rotary seal.

SUMMARY OF THE INVENTION

[0014] It is an object of the present invention to provide a multistage magnetic fluid seal having an increased pressure capacity. It is another object of the present invention to provide a multistage magnetic fluid seal having a geometric stage design that increases pressure capacity of the seal. It is a further object of the present invention to provide a multistage magnetic fluid seal having a geometric stage design that is less sensitive to axial misalignment than conventional multistage seals.

[0015] The present invention achieves these and other objectives by providing a multistage magnetic fluid seal having a rotary shaft, a ring-like magnetic assembly disposed around the rotary shaft forming air gaps, and ferrofluid disposed within the air gaps. The magnetic assembly has a first pole piece, a second pole piece and a permanent magnet between the first pole piece and the second pole piece. The first and second pole pieces are magnetically permeable as is the rotary shaft. The

rotary shaft is typically supported by high precision, lubricated bearings. A small radial gap or annulus is created between the rotary shaft and the first and second pole pieces.

[0016] In the multistage rotary seal of the present invention, the rotary shaft includes a plurality of ring-like grooves creating a plurality of ring like ridges. The plurality of ring-like ridges have a trapezoidal shape where the top of each ridge has a flat, plateau shape with sides that diverge away from the top to the bottom of the adjacent troughs. At least one of the pole pieces has a plurality of ring-like grooves creating a plurality of ring-like ridges. The pole piece ridges also have a trapezoidal shape. The plurality of shaft ring-like ridges are aligned to coincide with and be concentric with the plurality of pole piece ring-like ridges. Each opposed pair of the plurality of ring-like ridges forms a single stage of the multi-stage seal. The permanent magnet provides the magnetic field in the gap between the plurality of shaft ring-like ridges and the first and second pole pieces. The magnetic field is distributed such that there is a very high flux density in the annular volume of each stage of the multi-stage seal. The gap is filled with a ferrofluid. The flux density decreases to near zero a short distance away from each edge of each sealing stage in the multi-stage seal. The strong magnetic field gradients created by this change in flux density forces the ferrofluid back toward the high flux density region when the liquid O-ring created by the ferrofluid is subjected to a differential pressure.

[0017] A critical feature of the present invention is the cross-sectional shape of each of the plurality of ridges. The ridges have a trapezoidal shape where the sides or

legs of each ridge are tapered. The tapered sides diverge from the top of the ridge towards the base of the ridge.

[0018] The trapezoidal-shaped stage solves the problems seen in the prior art, geometrically-shaped stage. Prior art geometrically-shaped stages are either acute triangle stages, equilateral triangle stages or rectangular stages. In each prior art triangle-shaped stage, the pointed tip of the triangular shape focuses the magnetic flux field. However, the pointed tip of the triangle causes choking of the magnetic flux field strength. A prior art rectangular stage, on the other hand, reduces the choking inherent with the pointed triangular stages. A drawback of the rectangular stage is that it does not focus the magnetic flux within the gap as well as the pointed tip of the triangular stages.

[0019] The trapezoidal-shaped stage of the present invention provides the benefits of reduced chocking of the rectangular-shaped stage with increased focusing of the magnetic flux field of the triangular-shaped stage. The trapezoidal-shaped stage provides an angled or tapered stage that focus the magnetic field better than the rectangular stage, while simultaneously reducing the effects of triangular stage choking by providing a flat, top portion on the opposing ridges of each stage. The trapezoidal-shaped stage of the present invention provides a multi-stage seal having higher pressure capacity than similar multi-stage seals utilizing rectangular-shaped or triangular-shaped stages.

[0020] The advantages of trapezoidal stages over prior art rectangular stages are even more greatly enhanced when seals with high pressure capacity must be designed. When seals with high pressure capacity are designed, stronger magnets

are needed and used to generate strong magnetic fields. The stronger the magnet, the stronger and more dense the magnetic flux. At higher magnetic flux densities, the prior art rectangular-shaped stage begins to choke the magnetic flux more easily than the trapezoidal-shaped stage because the rectangular-shaped stage has higher resistance to magnetic flux.

[0021] In the preferred embodiment of the present invention, the second pole piece also has a plurality of ring-like ridges around the inside diameter of the second pole piece. The plurality of ring-like ridges of the rotary shaft are also aligned to coincide with and be concentric with the plurality of ring-like ridges of the second pole piece. Each pair of the plurality of opposed ring-like ridges forms a single stage of a multi-stage seal. The permanent magnet provides the magnetic field in the gap.

[0022] In this embodiment of the present invention, each of the plurality of opposed ring-like ridges of the second pole piece has the trapezoidal shape. Like the previous embodiment, the double, opposed trapezoidal-shaped stage increases the pressure capacity of the stage even greater than the single trapezoidal-shaped stage. These increases are both significant and unexpected. In addition, the double trapezoidal-shaped stage also maintains a greater pressure capacity over a larger amount of stage offset, i.e. misalignment, compared to a similar triangular-shaped double stage. This is very important in applications where double, opposed stages are used as stage offset occurs because various machining tolerances and assembling operations are involved.

BRIEF DESCRIPTION OF THE DRAWINGS

[0023] FIGURE 1 is a cross-sectional side view of a vacuum rotary ferrofluid seal incorporating the present invention.

[0024] FIGURE 2 is an enlarged, cross-sectional view of a portion of the pole pieces and rotary shaft of the present invention showing the trapezoidal-shaped stages formed into the shaft and the pole pieces.

[0025] FIGURE 3 is an enlarged, cross-sectional view of a portion of the pole pieces and rotary shaft of the present invention showing the trapezoidal-shaped stages formed in the shaft only.

[0026] FIGURE 4 is an enlarged, cross-sectional view of a portion of the pole pieces and rotary shaft of the prior art showing the rectangular-shaped stages formed into the shaft and the pole pieces.

[0027] FIGURE 5 is an enlarged, cross-sectional view of a portion of the pole pieces and rotary shaft of the prior art showing the rectangular-shaped stages formed in the shaft only.

[0028] FIGURE 6 is an enlarged, cross-sectional, side view of a seal having trapezoidal-shaped stages of the present invention formed into the shaft and the pole pieces showing the stages of the shaft and pole pieces in axial misalignment.

[0029] FIGURE 7 is an enlarged, cross-sectional, side view of a seal having triangular-shaped stages of the prior art formed into the shaft and the pole pieces showing the stages of the shaft and pole pieces in axial misalignment.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENT

[0030] The preferred embodiment of the present invention is illustrated in FIGURES 1-3 and 6. Figure 1 shows one embodiment of the present invention incorporated into a vacuum rotary seal **1**. A rotary seal housing **10** supports a rotary shaft **20** that is inserted into a vacuum chamber **12**. Rotary seal housing **10** is nonmagnetic and includes a ring-like magnetic assembly **30**. Magnetic assembly **30** is adapted to have a multi-stage seal **60** between rotary seal housing **10** and the rotary shaft **20**. Magnetic assembly **30** includes a first pole piece **32**, a second pole piece **35** and a permanent magnet **38** between first pole piece **32** and second pole piece **35**. First pole piece **32** and second pole piece **35** are magnetically permeable as is the rotary shaft **20**. Rotary shaft **20** is supported by high-precision, lubricated rolling element bearings **80** to maintain concentricity within the inside diameter of magnetic assembly **30**. A small radial gap, or annulus, **64** is created between rotary shaft **20** and first pole piece **32** and second pole piece **35**. Multi-stage seal **60** incorporates the trapezoidal-shaped stages of the present invention.

[0031] Turning now to Figure 2 there is illustrated an enlarged cross-sectional side view of multistage seal **60** having six trapezoidal-shaped stage pairs with each of first

pole piece **32** and second pole piece **35**. A quantity of magnetic fluid **62** is dispersed within the radial gap **64** located between the stages of shaft **20** and pole pieces **32**, **35**.

[0032] A plurality of trapezoidal-shaped stages **22** are formed into shaft **20**. Pole pieces **32** and **35** have a plurality of trapezoidal-shaped stages **33** and **36**, respectively, which oppose the plurality of trapezoidal-shaped stages **22** forming stages with double ridges. Permanent magnet **38** has a much larger inner diameter, which forms a large radial gap between magnet **38** and rotary shaft **20**.

[0033] Each trapezoidal-shaped stage **22**, **33** and **36** has a plateau portion **40** and tapered sides **42** that diverge from each other away from plateau portion **40** toward an annular region **44**. Tapered sides **42** are generally of equal length and may diverge over a range of angles so long as plateau portion **40** and sides **42** do not form right angles. Logically, the tapered sides must diverge at an angle between 0° and 180°.

[0034] The final shape of each of the plurality of trapezoidal-shape stages is optimized for the pressure capacity needed for a given application for seal **1**.

[0035] In the tables presented herein, the pressure capacity for each stage was determined using the magnetic field calculating software known as the MAGNETO Two-dimensional Magnetic Field Solver Version 3.1 software available from Integrated Engineering Software, Inc., Winnipeg, Manitoba, Canada. The MAGNETO software employs the Boundary Element Method of calculating boundary value problems using the boundary integral equation formulation.

[0036] A variety of variables may be inputted into the MAGNETO software to calculate the magnetic field strength for a given geometric stage design. The variables for a magnetic fluid seal that can be adjusted within the MAGNETO 3.1 software include the stage shape, the stage location, the pole length, the pole outer diameter, the radial gap distance, the eccentricity of the shaft to the magnet and poles, the pole material, the shaft material, the shaft inner and outer diameters, the magnetic fluid, and the magnet material and magnet dimensions.

[0037] For the present invention, the width (w) and depth (d) of the trapezoidal-shaped stage is inputted into the MAGNETO 3.1 software. Other variables within the magnetic fluid seal were held constant to compare the unexpected enhanced capacity of the single and dual trapezoidal stages over magnetic fluid seals with prior art rectangular-shaped and triangular-shaped stages. The properties of Ferrotec fluid #VSG 803, available from Ferrotec (USA) Corporation, Nashua, NH, with a saturation magnetization value of 450 Gauss and a single ring-shaped Neodymium Iron Boron magnet, size 34, was used to compare the values determined in Tables 1-4.

[0038] Particularly for Tables 1-4, the following variables were fixed.

Pole Material = Stainless Steel	**Shaft Material = Stainless Steel**	
Pole Length = 2.01 inch	**Shaft OD = 2.002 inch**	**Tooth Width = 0.01 inch**
Radial Gap = 0.004 inch	**Shaft ID = 0.001 inch**	**Tooth Depth = 0.025 inch**
Graph Position = 0.001 inch from Pole		

[0039] Table 1 shows the magnetic field intensity in Oersteds of a magnetic seal incorporating sixteen trapezoidal-shaped stage pairs where eight stage pairs are formed with each pole piece.

Table 1 - MAGNETIC FIELD AND SEALING CAPACITY OF DUAL TRAPEZOIDAL STAGE DESIGN

Stage#	Max Air Gap Hg (Oersted)	Min Air Gap Hg (Oersted)	Average Gap Hg (Oersted)	Ave. Magnetic Fluid Strength (Gauss)	Stage Pressure Capacity (PSI)
Pole #1 - Vacuum Outside to Magnet					
1	20412	5371	12891.5	435	7.65
2	20494	6734	13614	436	7.01
3	20472	6720	13596	436	7.01
4	20477	6705	13591	436	7.02
5	20522	6766	13644	436	7.01
6	20527	6767	13647	436	7.01
7	20541	6780	13660.5	436	7.01
8	20498	6776	13637	436	6.99
Ave. Values	20493	6577	13535	----	7.09
			Tot. PSI for Pole #1		56.7
Pole #2 - Magnet to Atmospheric Side					
9	20262	5404	12833	435	7.56
10	20412	6583	13497.5	435	7.05
11	20402	6629	13515.5	435	7.02
12	20453	6630	13541.5	436	7.04
13	20446	6676	13561	436	7.02
14	20454	6685	13569.5	436	7.02
15	20480	6701	13590.5	436	7.02
16	20405	6727	13566	436	6.97

Ave. Values	20414	6504	13459	-------	7.09
			Total PSI for Pole #2		56.7
				Total PSI for Seal	**113.4**

[0040] As disclosed in Table 1, the highest average magnetic field strength of a single stage pair was approximately 20,500 Oersteds. The lowest average magnetic field strength was approximately 6550 Oersteds. The average differential magnetic field strength for each tapered stage pair was 13,500 Oersteds.

[0041] The pressure capacity for each trapezoidal stage pair is proportional to the differential magnetic field strength for that stage pair. Accordingly, the average differential magnetic field strength of 13,500 Gauss corresponds to an average stage pressure capacity of 7.09 pounds per square inch for each stage pair. The pressure capacity for each trapezoidal stage pair is summed to increase the overall pressure differential of seal **60** by the total added capacity of the summed pairs of stages. Thus, the placement of sixteen trapezoidal stage pairs within seal **60** provides a total pressure capacity for seal **60** of 113.4 pounds per square inch.

[0042] Turning now to Figure 3 there is illustrated an enlarged cross-sectional side view of a prior art multistage seal **60** having six trapezoidal-shaped stages situated adjacent to first pole piece **32** and second pole piece **35**. Only the shaft has the trapezoidal-shaped stages. It is noted that the pole pieces may have the trapezoidal-shaped stages with the shaft having a smooth circumferential surface. A quantity of magnetic fluid **62** is dispersed within the radial gap **64** located between the stages of shaft **20** and the smooth surface **32'** and **35'** of pole pieces **32, 35**, respectively.

[0043] A plurality of trapezoidal-shaped stages **22** are formed into shaft **20**. Permanent magnet **38** has a much larger inner diameter, which forms a large radial gap between magnet **38** and rotary shaft **20**. Each trapezoidal-shaped stage **22** has a shape similar to that disclosed in Fig. 2, which includes a plateau portion **40** and tapered sides **42** that diverge from each other away from plateau portion **40** toward an annular region **44**. Tapered sides **42** are generally of equal length and may diverge over a range of angles so long as plateau portion **40** and sides **42** do not form right angles.

[0044] To maintain consistency with the data, Table 2 shows the magnetic field intensity in Oersteds of a magnetic seal incorporating sixteen trapezoidal-shaped stages where eight stages are formed with each pole piece and where only the shaft has the trapezoidal-shaped stage.

Table 2 - MAGNETIC FIELD AND SEALING CAPACITY OF SINGLE TRAPEZOIDAL STAGE DESIGN

Stage#	Max Air Gap Hg (Oersted)	Min Air Gap Hg (Oersted)	Average Gap Hg (Oersted)	Average Magnetic Fluid Strength (Gauss)	Stage Pressure Capacity (PSI)
Pole #1 - Vacuum Outside to Magnet					
1	18368	7653	13010.5	435	5.45
2	18615	9193	13904	436	4.81
3	18816	9453	14134.5	436	4.78
4	18681	9438	14059.5	436	4.72
5	18576	9342	13959	436	4.71
6	18316	9251	13783.5	436	4.62
7	18314	8983	13648.5	436	4.76
8	18352	8933	13642.5	436	4.80

Ave. Values	18504.8	9030.8	13767.8	----	4.83
			Total PSI for Pole #1		38.6
Pole #2 Magnet to Atmospheric Side					
9	18197	7181	12689	435	5.60
10	18272	8923	13597.5	436	4.76
11	18162	8878	13520	436	4.73
12	18482	9194	13838	436	4.74
13	18636	9347	13991.5	436	4.74
14	18823	9450	14136.5	436	4.78
15	18699	9492	14095.5	436	4.70
16	18421	9253	13837	436	4.67
Ave. Values	18461.5	8964.75	13713.1	-------	4.84
			Total PSI for Pole #2		38.7
			Total PSI for Seal		**77.4**

[0045] As disclosed in Table 2, the highest average magnetic field strength of a single trapezoidal stage was approximately 18,500 Oersteds. The lowest average magnetic field strength of a single trapezoidal stage was approximately 9,000 Oersteds. The average differential magnetic field strength for each single trapezoidal stage was 13,700 Oersteds.

[0046] The pressure capacity for each single trapezoidal stage, just as for the dual stage pair, is proportional to the differential magnetic field strength for that single stage. Accordingly, the average differential magnetic field strength of 13,700 Oersteds corresponds to an average single stage pressure capacity of 4.835 pounds per square inch for each single trapezoidal stage. The pressure capacity for each

single trapezoidal stage is summed to increase the overall pressure differential of seal **60** by the total added capacity of the summed single stages. Thus, the placement of sixteen single trapezoidal stages on shaft **20** of seal **60** provides a total pressure capacity for seal **60** of 77.4 pounds per square inch.

[0047] Figure 4 illustrates an enlarged cross-sectional side view of a prior art, multistage seal **160** having six rectangular-shaped stage pairs between a shaft **120** and a first pole piece **132** and a second pole piece **135**. A quantity of magnetic fluid **162** is dispersed within a radial gap **164** located between the stages of shaft **120** and pole pieces **132**, **135**. A plurality of rectangular-shaped stages **122** are formed into shaft **120**. Pole pieces **132** and **135** have a plurality of rectangular-shaped stages **133** and **136**, respectively, which are in an opposed relationship with the plurality of rectangular-shaped stages **122** forming stages with double ridges. Permanent magnet **138** has a much larger inner diameter, which forms a large radial gap between magnet **138** and rotary shaft **120**. Each rectangular-shaped stage **122**, **133** and **136** has a plateau portion **140** and perpendicular sides **142** that issue away from plateau portion **140** toward an annular region **144**. Perpendicular sides **142** are generally of equal length and form right angles with plateau portion **140**.

[0048] Table 3 shows the magnetic field intensity in Oersteds of a magnetic seal incorporating sixteen rectangular-shaped stage pairs where eight stage pairs are formed with each pole piece.

Table 3 - MAGNETIC FIELD AND SEALING CAPACITY OF DUAL RECTANGULAR STAGE DESIGN

Stage#	Max Air Gap Hg (Oersted)	Min Air Gap Hg (Oersted)	Average Gap Hg (Oersted)	Ave. Magnetic Fluid Field Strength (Gauss)	Stage Pressure Capacity (PSI)
Pole #1 - Vacuum Outside to Magnet					
1	14208	5296	9752	430	4.49
2	14262	5702	9982	431	4.31
3	14276	5635	9955.5	431	4.35
4	14306	5699	10002.5	431	4.34
5	14372	5650	10011	431	4.39
6	14561	5611	10086	431	4.51
7	14504	5568	10036	431	4.50
8	14075	5526	9800.5	430	4.30
Ave. Values	14320.5	5585.9	9953.2	------	4.40
			Total PSI for Pole #1		35.2
Pole #2 - Magnet to Atmospheric Side					
9	14213	5321	9767	430	4.48
10	14896	5651	10273.5	431	4.66
11	14710	5635	10172.5	431	4.58
12	14712	5634	10173	431	4.58
13	14462	5630	10046	431	4.45
14	14233	5602	9917.5	430	4.35
15	14262	5675	9968.5	431	4.33
16	14152	5659	9905.5	430	4.28
Ave. Values	14455	5600.9	10027.9	-------	4.46
			Total PSI for Pole #2		35.7
			Total PSI for Seal		**70.9**

[0049] As disclosed in Table 3, the highest average magnetic field strength of a single stage pair was approximately 14,385 Oersteds. The lowest average magnetic field strength was approximately 5,600 Oersteds. The average differential field strength for each stage was approximately 10,000 Oersteds. The pressure capacity for each rectangular stage pair was approximately 4.43 pounds per square inch. The pressure capacity for each rectangular stage is summed to increase the overall pressure differential of the seal by the total added capacity of the summed stages. In the case of the rectangular stage pairs placed along the shaft and the poles, the pressure capacity of the seal provides a total pressure capacity of approximately 70.9 pounds per square inch.

[0050] The pressure capacity of 113.4 pounds per square inch for the seal with sixteen trapezoidal stage pairs is 1.6 times higher than the pressure capacity of 70.9 pounds per square inch for the seal having sixteen prior art rectangular stage pairs.

[0051] Turning now to Figure 5, there is illustrated an enlarged, cross-sectional side view of multistage seal **160** having six rectangular-shaped stages situated adjacent to first pole piece **132** and second pole piece **135**. A quantity of magnetic fluid **162** is dispersed within the radial gap **164** located between the stages of shaft **120** and the smooth surface **132'** and **135'** of pole pieces **132**, **135**, respectively.

[0052] A plurality of rectangular-shaped stages **122** are formed into shaft **120**. Permanent magnet **138** has a much larger inner diameter, which forms a large radial gap between magnet **138** and rotary shaft **120**. Each rectangular-shaped stage **122** has a shape similar to that disclosed in Fig. 4, which includes a plateau portion **140**

and perpendicular sides **142** that issue away from plateau portion **140** toward an annular region **144**. Perpendicular sides **142** are generally of equal length and form right angles with plateau portion **140**.

[0053] Table 4 shows the magnetic field intensity in Oersteds of a magnetic seal incorporating sixteen rectangular-shaped stages where eight stages are formed with each pole piece and only the shaft has the rectangular-shaped stage.

Table 4 - MAGNETIC FIELD AND SEALING CAPACITY OF SINGLE RECTANGULAR STAGE DESIGN

Stage #	Max Air Gap Hg (Oersted)	Min Air Gap Hg (Oersted)	Average Gap Hg (Oersted)	Ave. Magnetic Fluid Strength (Gauss)	Stage Pressure Capacity (PSI)
Pole #1 - Vacuum Outside Inward to Magnet					
1	15235	8583	11909	434	3.37
2	15250	8441	11845.5	434	3.45
3	15242	8322	11782	433	3.51
4	15240	8395	11817.5	433	3.47
5	15228	8343	11785.5	433	3.49
6	15162	8321	11741.5	433	3.47
7	15092	8284	11688	433	3.45
8	15116	8279	11697.5	433	3.47
Ave. Values	15196	8371	11783	----	3.46
			Total PSI for Pole #1		27.7
Pole #2 - Magnet to Atmospheric Side					
9	15313	8424	11868.5	434	3.49
10	15263	8448	11855.5	434	3.46
11	15273	8405	11839	434	3.48
12	15221	8380	11800.5	433	3.47

13	15190	8321	11755.5	433	3.48
14	15200	8297	11748.5	433	3.50
15	15154	8317	11735.5	433	3.47
16	15117	8384	11750.5	433	3.41
Ave. Values	15216	8372	11794	-------	3.47
			Total PSI for Pole #2		27.8
			Total PSI for Seal		55.5

[0054] As disclosed in Table 4, the highest average magnetic field strength of a single rectangular stage was approximately 15,200 Oersteds. The lowest average magnetic field strength of a single trapezoidal stage was approximately 8,400 Oersteds. The average differential magnetic field strength for each single rectangular stage was 11,790 Oersteds.

[0055] The pressure capacity for each single rectangular stage, just as for the dual stage pair, is proportional to the differential magnetic field strength for that single stage. Accordingly, the average differential magnetic field strength of 11,790 Oersteds corresponds to an average single stage pressure capacity of 3.50 pounds per square inch for each single rectangular stage. The pressure capacity for each single rectangular stage is summed to increase the overall pressure differential of the seal by the total added capacity of the summed single stages. Thus, the placement of sixteen single trapezoidal stages on shaft **120** provides a total pressure capacity of approximately 55.5 pounds per square inch.

[0056] The total pressure capacity of a seal with sixteen double trapezoidal stages, as shown in Table 1, is 113.4 pounds per square inch. The total pressure capacity of

a seal with sixteen prior art double rectangular stages, as shown in Table 3, is 70.9 pounds per square inch. The increase in total pressure capacity of a seal with sixteen double trapezoidal stages is approximately 1.6 times greater than the seal with prior art double rectangular stages. This increase in stage capacity was quite unexpected.

[0057] A comparison was also performed between seals having double trapezoidal-shaped stages and double triangular-shaped stages. The total pressure capacity for these two types of seals was determined for a seal having 20 stages where the stage pairs were radially concentric and axially concentric and where the stage pairs were radially concentric and had an axial offset.

[0058] Figure 6 is an enlarged, cross-sectional, partial side view of a multistage seal **60** having twenty trapezoidal-shaped stage pairs. The depth **200** of each tapered stage is 0.025 inch. The width of the plateau portion **40** is 0.015 inch. Axial offset is represented by reference numeral **210**.

[0059] Figure 7 is an enlarged, cross-sectional, partial side view of a multistage seal **60** having twenty triangular-shaped stage pairs. The depth **200'** of each triangular stage is 0.025 inch. Because the shape of the stage is triangular, there is no plateau portion on the stage. Axial offset for the triangular-shape pairs is represented by reference numeral **210'**.

[0060] Particularly, for Table 6, the following variables were fixed.

Magnet = Neodymium Iron Boron 34	**Radial Gap = 0.0056 inch**
Pole Material = Stainless Steel	**Shaft Material = Stainless Steel**
Pole OD = 2.342 inch	**Shaft OD = 1.0 inch**

Pole ID = 1.012 inch **Shaft ID = 0.00 inch**

Tooth Depth = 0.025 inch **Tooth Pitch = 0.06 inch**

[0061] Table 6 shows the pressure capacity comparison for a seal with 20 double stages having axial offsets of the stages between the shaft and the pole pieces in the range from 0.0 inch to 0.015 inch.

Table 6 – Effect of Stage Shape on Pressure Capacity

Axial Offset (Inch)	Trapezoidal Shape Pressure Capacity (PSI)	Triangular Shape Pressure Capacity (PSI)
0.0	79.36	69.85
0.005	81.59	62.05
0.010	85.47	48.39
0.015	78.24	39.23

[0062] As can be seen from Table 6, the double trapezoidal-shaped multistage seal provides 13% more pressure capacity compared with the double triangular-shaped multistage seal at the axial concentric position with 0.0 offset. More importantly, when some axial offset exists (which is always the case in real-world seals due to part dimensional tolerances), the difference between the two stage geometries increases significantly. The pressure capacity of the double triangular-shaped stage decreases substantially, while the pressure capacity of the double trapezoidal-shaped stage maintains its value or even increases slightly when the offset is not too large.

[0063] The proffered reason for the superior performance of double trapezoidal-shaped stages is that each tooth of the individual stages has more area facing the mating tooth making it less likely to be magnetically choked. This characteristic also makes the double trapezoidal-shaped stage less sensitive to the axial offset because

the effective sealing gap does not change with the offset (within certain offset limits). In comparison, the sealing gap of the double triangular-shaped stage increases significantly with the increase of axial offset.

[0064] Although the preferred embodiments of the present invention have been described herein, the above description is merely illustrative. Further modification of the invention herein disclosed will occur to those skilled in the respective arts and all such modifications are deemed to be within the scope of the invention as defined by the appended claims.